GEORGIA INSTITUTE OF TECHNOLOGY
Engineering Experiment Station
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Investigations Undertaken between 28 September 1961 and 28 September 1962

During the past year, work in the Space Sciences area has advanced considerably and the support given by the National Sciences Foundation has served as an essential foundation for this work.

The specific objective of our proposal to the NSF in 1960 was the study of "Shock Wave Phenomenon in the Upper Atmosphere." The supply of experimental data for these studies has been somewhat scarce since the explosions in space which occurred in the summer and fall of 1960 under Air Force Project Firefly did not produce as many shock waves as had been expected. Some data was obtained and the results are given in a preliminary report. The abstract of this report is presented here.

Spherical Wave from Explosive Burst at High Altitude

L. C. Young, H. D. Edwards, M. T. Capps

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ABSTRACT Rapidly growing, short-lived spherical waves have been observed emanating from explosive releases in the upper atmosphere. Study of the conditions of explosion indicates that the waves may consist of the fragments of aluminum canister which have been dispersed at extremely high velocity.

The above report has not yet been submitted for publication since we are awaiting more data from the next Firefly series which is scheduled to begin on October 15, 1962.

Theoretical studies and improved instrumentation pertaining to the shock wave problem have been carried out. As a result, our group will be better equipped to gather data and will have a better understanding of the data obtained from the rocket firings this fall.

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One of the most important objectives of the Space Sciences program at Georgia Tech is to create a stimulating environment for teaching and research in the atmospheric and space sciences.

Eleven students, both graduate and undergraduate, have been assisted either directly or indirectly by the NSF support. One Master of Science degree in Physics will be obtained next spring and several other graduate students are in the program and will obtain advanced degrees at a later date.

A graduate course in "Physics of the Upper Atmosphere" has been added to the curriculum of the School of Physics and will be offered by Dr. Edwards during 1962-1963.

Future Investigations

Shock wave data obtained from the 1962 Firefly series will be analyzed and the results published if feasible.

Teaching and research in the atmospheric and space sciences will continue to be emphasized at both the graduate and undergraduate levels.

Respectfully submitted,

Howard D. Edwards
Research Associate Professor of Physics

FINAL REPORT

PROJECT B-199

SHOCK WAVE PHENOMENON IN THE UPPER ATMOSPHERE

H. D. EDWARDS AND L. C. YOUNG

Grant No. NSF-G14783

Prepared for

Atmospheric Sciences Branch
National Science Foundation
Washington 25, D. C.

December 1963

Engineering Experiment Station
GEORGIA INSTITUTE OF TECHNOLOGY
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Final Report

Georgia Tech Project No. B-199

Shock Wave Phenomenon in the Upper Atmosphere

by

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Introduction

The objective of the initial proposal was to determine the effect of the interaction of spherical shock waves with the ambient atmosphere at altitudes in excess of 100 km. Shock waves had been observed visually during rocket firings which took place in April 1959, and since similar firings were planned later that year and for the following year, the scope of this study was to include the analyses of shock wave data obtained during these latter series of firings. The rocket experiments were planned primarily to create luminous ionized clouds for atmospheric motion and radio frequency studies by releasing chemicals into the upper atmosphere. Hence, data for the shock wave study were to come primarily as a by-product produced by the detonation material used to create the chemical cloud.

Results from the studies have been very discouraging. The project has been plagued by several shortcomings. (1) The three rocket payloads assigned entirely to pure high explosive studies in 1962 failed. (2) The high explosive used in the chemical release payloads of 1960 and 1962 series failed to produce shock waves similar to the April 1959 series. (3) Rocket position prediction at the time of chemical release was unreliable and hence the photometer could not be aimed correctly to detect the transient luminous pulse. (4) Some limitations on instrumentation became apparent only during attempted data analysis.

One publication has resulted from the work and is as follows: "Field Photometer with Nine Element Filter Wheel," Z. Frentress, L. C. Young, and H. D. Edwards, Applied Optics, December 1962.

Exhaustive attempts were made to achieve publishable results from the data taken, or lack of it, on rocket firings which took place in 1959, 1960, and 1962. A very limited account will be given of the negative results which were obtained, and those areas of endeavor which appear useful for future studies of the shock wave phenomenon at high altitude will be described briefly.

Late in the grant period a Ph.D. thesis on diffusion coefficients in the upper atmosphere was initiated and the proposed work will be described.

Background

In review, it was our purpose to determine the cause and nature of certain rapidly moving, luminous spherical wave fronts which had been observed during the Firefly releases of April 1959. The most puzzling aspect of these waves was the rate of radial propagation, which was constant at nearly 4 km/sec over the first 2 seconds, after initiation and until the wave could no longer be detected. The constancy of that rate suggested that the wave was propagated without dissipation of energy, as contrasted with a spherical shock wave propagated in air (e.g. "Blast Wave from a Spherical Charge," H. L. Brode, Physics of Fluids 2, no. 2, 217-229, March 1959). It was believed that spectral information was necessary to give a clue as to the source of a phenomenon so unexplainable on the basis of known mechanisms of wave propagation.

It is worth noting that, in "Initial Expansion to Ambient Pressure of Chemical Explosive Releases in the Upper Atmosphere," (G. V. Groves, Journal of Geophysical Research 68, no. 10, 3033-3047, May 1963) the question of an air borne shock wave has been examined. Although some of the details in the concepts therein are subject to question, the main result may be interpreted, here, as a finding that the initial rate of propagation of a shock wave decreases with altitude. The shock wave with which Groves is concerned is closely associated with (i.e. generally less than 0.1 km away from) the expanding surface of the gases from the exploded release, starting at a rate of 2 km/sec and decreasing to a substantially lower rate within 0.5 second. Although the propagation rate was not explicitly given therein, the gas cloud data discussed there suggest that it follows the form developed by Taylor (cf, e.g., A. H. Taub, Handbook of Physics, p. 3-61, equation 4.87). Whether or not this shock wave is visually distinguishable from the gas cloud for which it forms a front, it is clearly distinguishable as a phenomenon from the rapidly propagated luminous wave with which we have been concerned.

The very high rate of the latter has led during the course of this study to some speculation that it might have been caused by particles formed by fragmentation of the aluminum container upon explosion. Appendix 1 comprises an analysis confirming that such a rate could have occurred, with small fragments being accelerated to a velocity of approximately 3.3 km/sec. The method underlying this result was too primitive to warrant publication, but was sufficient to leave no doubt as to the accuracy of the conclusion. The source of the luminescence would, of course, remain unexplained in that instance except by means of some further hypothesis. One such possible explanation, that aluminum vapor moving with the exploded particles could have produced resonant lines 3944 Å and 3962 Å under solar excitation, arose during study of a release of a different type, and has been reported in "Alumina Dispersal at 150 km Altitude, an Analysis of the Photographic Record," L. C. Young, AFCRL 63-466, February 1963.

In order to determine whether a similar mechanism could have underlain the luminescence of the waves seen in 1959, spectral information would have been necessary. Failure to obtain it in either positive or negative form during the 1962 releases has prevented formation of any definite conclusion.

Instrumentation

During the early phases of the study, it was determined that the instrumentation used in the late 1959 and 1960 series did not give adequate data to determine spectral characteristics of the luminous glow created by the shock wave interaction with the ambient atmosphere. Hence, considerable effort was devoted to the development of an instrument which would provide acceptable data. The instrument developed was a field photometer with a nine element filter wheel. An article describing the instrument is to be published in the December 1963 issue of <u>Applied Optics</u>. The abstract is presented here and reprints will be forwarded when they are received.

Field Photometer With Nine Element Filter Wheel
by Z. Frentress, L. C. Young, and H. D. Edwards

A field photometer consisting of a single photomultiplier tube and a nine element filter wheel has been designed and used to study low-light levels of the order of 10^{-11} W/cm^2 sr. The filter wheel can be operated up to 10 rps to give data from each spectral region at a rate of 10 times per second. Light is collected by a 500 mm diam. f/1.1 parabolic mirror and after being rendered parallel by a suitable lens system, passes through filters to a photomultiplier. A description and operating characteristics of the instrument are given. Sample data taken on a recent field test are presented, as are photographs of key items in the instrument.

Several applications, modifications, and limitations of the photometer have been suggested as a result of the work to date. These will be discussed in the section on suggestions for future work.

Data Obtained

Of the 24 rocket launches for which the photometer was usefully employed in Firefly III, October-December 1962, (i.e. excluding daytime releases and payloads which failed to ignite) two or three gave signals from which no spectral inferences could be drawn at any time during the experiment. Of the other releases, the spectral distribution of the initial signal was that of sky background and the subsequent signal was a continuum compatible with the sum of sky background and gas release. There was no signal component which could be reasonably attributed to a rapidly moving luminous wave. During the first 11 of these, erratic intensity measurements from the standard lamp used for calibration, and in some cases in the background sky measurement, tended to destroy confidence in the absolute magnitude of the intensity readings. Furthermore, none of these had both an associated photographic record of the field being viewed and a time signal indicating the time of the view.

During the remainder of the series, calibration measurements were satisfactory and the majority of sky background measurements corresponded to those reported by Hulburt (Brightness of the Twilight Sky and Density and Temperature of the Atmosphere, J.O.S.A. 28, 227-236, 1938) or determined by photographic densitometric means. Of these 13 remaining rockets, however, 6 did not have photographic coverage on the Automax camera mounted with the photometer. When the field of view of the photometer is changing (as it is when the photometer is being redirected or when a release is expanding or changing its shape or position), a photographic record is necessary in order to interpret the nature of the photometer output and to distinguish between flares, stars, drift, and expansion. This is particularly true when the release experiment consists of more than one luminescent release in chronological sequence. Only when the Automax was run at 1 frame every 2 seconds were the time signals visible on the film for correlation of the photometer output to the film record, and this meant that the photograph could be dependably interpreted only when the field was not changing substantially during the course of the 2-second interval.

As a result of the foregoing, the spectral signals coming from the photometer during most of the initial bursts of the 1962 Firefly III releases pertained to sources which could not be identified with any reasonable reliability. Therefore, although a photometric record existed which showed the signal sensed through each of the filters, its absolute magnitude was initially in question, and uncertainty as to the signal source prevented formation of conclusions relative to transient signals such as might have been caused by a luminous wave ahead of the expanding gas cloud.

Results of the Data Obtained

Of the Fall-Winter 1962 releases of Firefly III, there were seven for which there was also photographic coverage including a time signal and view of the reticle: they were rocket numbers 24, 26, 28, 29, 30, 31, and 32. On each of these, the photographic film exposure was 2 sec/frame, and the filter wheel speed was 1.6 rev/sec. Further details are:

With No. 24, apparently the photometer and camera were sighting on a rocket borne flare prior to and until 3 seconds after this TEC release, which took place about 2° away from the line-of-sight; the photometer was redirected and picked up the main release at 5 or 6 seconds after it originated. The signals recorded can be attributed to one or the other of these two sources: i.e., there was no evidence of a third signal capable of being separated from the others and which might have been caused by a shockwave.

No. 26 was a release of nitric oxide, throttled, from a pressurized tank, and therefore not expected to give rise to shockwaves. The photometer was directed to within 3° of the release at time of initiation; no response was obtained until 3 seconds later, by which time the photometer and camera had been redirected to the glowing cloud for readings of about 2 seconds duration. The amplifier then overloaded and remained so for the next 15 seconds. The recorder trace was very faint throughout this run--enough so to shed considerable doubt on the true magnitudes of many of the readings.

No. 28 was also a nitric oxide release. This occurred within 2° of the direction in which the photometer was sighted. No signal was obtained during the 2.5 seconds in which the photometer was redirected; then 5 seconds of signal were recorded, but the recorder trace is extremely faint. Three of the nine filter cells gave off-scale readings during this time. For the next 17 seconds, the amplifier was overloaded.

No. 29 consisted of the release of seven grenades, after which the photometer was turned off. The grenades were released over an 11 second interval. The photometer was 2° off-sight at the first burst, was redirected and received its first signal at 3 seconds after burst. Since three or four of the grenades were clustered within 0.5°, it is not clear which parts of which bursts were being sensed by the photometer scan.

No. 30 possessed a payload consisting of alternate layers of an explosive mixture and layers of coarse aluminum granules (36% of total, by weight). The recorder was turned on 2.6 seconds after the burst had occurred at a point 7.5°

away from the photometer line-of-sight and at a slant range of 109 km. At 10 seconds after burst, redirection of the instrument was started to bear upon the burst; this was completed in 10 more seconds. Not until that time was any signal apparent on the recorder tape, above background. Had a luminous ring increased in radius and passed the sight of the photometer during this period, it would have needed to subtend at the photometer a radial breadth of 0.4° with radiance of only 2×10^{-10} watts/cm^2 steradian (at any of those wavelengths at which all but the Wratten 25 and the 5825 interference filters had peak response) to allow positive evidence of its presence, in the form of a 0.04 inch further deflection of the galvanometer trace. It is worth noting that the most extreme waves sensed (but not spectrophotometrically) in the 1959 releases had vanished by the time that they had reached 13 km at the maximum--a distance almost equal to the normal between the burst of No. 30 and the line-of-sight of the photometer.

Nos. 31 and 32 both consisted in the release of acetylene by the same means as employed in No. 26. The first of the pair occurred at a point 4° from the line-of-sight of the photometer; redirection was started 4 seconds later and finished at 9 seconds after the acetylene release was initiated. The first signal evident above background in the galvanometer recorder trace occurred at 6 seconds after burst, but this signal was a transient which may be attributed to the process of redirecting the photometer. At 9 seconds after initiation, the amplifier overloaded--presumably from a much larger signal from the cloud--and remained so for the next 12 seconds, by which time the amplifier gain had been reduced to one-fifth its previous value.

With No. 32, the photometer was being redirected from the time of burst until 16 seconds thereafter, at which time a continuing signal was obtained without overload. During the first 16 seconds, two separate transients occurred, but both may be attributed to having the line-of-sight of the photometer hover about the point at which it was finally aimed.

In summarizing the findings on the foregoing releases, with respect to the investigation of shock waves in the upper atmosphere, it is apparent that four of the releases (26, 28, 31, and 32) were of pressurized gas; one (24) was a trail electron cloud generated by a high temperature, low pressure reaction occurring over 100 seconds; one (29) was of seven grenades, each containing 19 grams of an explosive mixture; and one (30) contained 6.6 kg of a high explosive. Only the latter possessed the energy and rate of release comparable to those bursts which were believed to have originally given rise in 1959 to shock waves.

It is extremely disappointing that the three rocket payloads specifically assigned to pure, high explosive should have been among the five which failed to operate out of the 33 experimental launches. Almost equally distressing is the fact that the one fully photometered experimental release which had a payload promising to simulate earlier sources of hypothesized shock waves (No. 30) had veered so much from its scheduled burst point that it was essentially outside the field of potential observation.

Suggestions for Future Work

The interaction of spherical shock waves with the ambient is an important and still unsolved problem in upper atmosphere physics. It is believed that the most practical way of approaching this problem is to take a high explosive to altitude, detonate it and observe the luminous reaction from ground stations. Several suggestions which might assist the next investigator will be made as a result of our unsuccessful attempt to solve this problem.

(1) The luminous shock wave is a transient phenomena lasting only a few seconds and moving outward only 5° or so from the explosion center before being dissipated. Hence, the instrument used to observe this advancing luminous front must be extremely fast optically (probably photoelectric) and directed to an azimuth and elevation which is only a few degrees from the explosion center.

Hence, azimuth and elevation settings are extremely important and must be set in advance of the explosion since there is not sufficient time to redirect the instrument before the event is over. A serious limitation in this study has been the unpredictability of the rocket trajectory and hence, the inability to set correct azimuth and elevation. New methods of firing payloads to the 100 km level with greater accuracy than is possible with the Nike-Cajun and Nike-Apache type rockets is needed. At present, the Army Ballistic Research Laboratory and McGill University are developing a 16.4 inch gun which appears to have the predictability of trajectory required to give advance azimuth and elevation settings.

(2) Some deficiencies still exist in the photometer which was used in this work. In its current configuration, the photometer is fitted with an Automax camera, with reticle displaying a 5° (diameter) ring and center cross, plus provision for recording a time signal. In the field work of 1962, only those films having a 2 second exposure were adequate in recording the release and time signal. The line-of-sight was on the line of the ring for the middle of the scanning range of each frame, and some of the releases had their time signal wholly along the line of the sprocket holes, making it difficult or impossible to read.

Inasmuch as the field of view being scanned is $0.4^{\circ} \times 2^{\circ}$, (i.e. a 0.4° diameter circle moving over an arc of about 2° with partial increasing eclipse beyond this), accurate boresighting may require some special technique. A point source such as a star will give a signal from anywhere in this field. Precise knowledge of the direction in which the photometer is pointed might perhaps be most easily obtained by substitution of a .03 inch diameter diaphragm in one of the collimating cells, together with accurate positioning of the wheel so that the cell is in the middle of its scan range, coaxial with the photomultiplier tube. For comparable precision on the photographic record, it would be desirable to change the reticle to one with corner crosses, leaving the field of view clear. Alignment of the axis of the camera lens with that of the photometer is necessary. The chief requirement is to be able, after a series of releases, to know the precise 0.4° area within each photographic frame from which a given signal was obtained at a given instant, or the precise $0.4^{\circ} \times 2^{\circ}$ rectangular scan area yielding a given signal trace at the time of the photograph.

During the course of a release, if the photometer is being redirected at the time that an interesting series of signals is obtained, it would be desirable to match the signals with the photographic subject. In that case, a 2 second exposure is quite a bit too long, even for the slow wheel speed of 100 rpm used during the majority of the 1962 releases. However, it becomes important in that case to record all transient sources such as stars, which would yield a photometer signal although their images would not be recorded on the film. To obtain a picture of the transient, a combination of an image intensifier and Mod IV camera could be installed on the photometer.

A decided downward trend in the signal from the calibration light, over the course of the 1962 releases, leveling out at one-third its initial value, remains unexplained. Similar inexplicabilities occurred to a less frequent extent in the ratios of background intensity actually recorded to that expected at the given angle of solar depression: the ratio has been as great as ten to one and as low as one-tenth. Although there is no evidence of incorrect entry in the log of tube voltage or amplifier gain, it seems quite possible that such an error could occur among the many variables recorded for each release.

The majority of the 1962 releases gave strong continua. To increase the chance of detecting lines or bands above this with a galvanometer reading that may be kept on scale, it is desirable that the backgrounds and the continua give approximately the same response through each of the filter openings. In the 1962 releases, all openings but those of the two longest wave lengths had very nearly the same peak response (considered as a product of filter cell transmission times photomultiplier sensitivity). To keep the same field of view for each filter while obtaining a uniform total response among the nine openings, it is recommended that the response from any wide band filter (e.g. Wratten) used in the future be reduced by use of "neutral" density filters. This is especially true if both wide band (Wratten) and narrow band (interference) filters are used simultaneously. If neutral density filters are used, it is suggested that each one have a density equal to the logarithm (base 10) of the ratio, of the half power width of that wide band filter to those of the interference filters otherwise used.

APPENDIX 1

Spherical Wave from Explosive Burst at High Altitude

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ABSTRACT Rapidly growing, short-lived spherical waves have been observed emanating from explosive releases in the upper atmosphere. Study of the conditions of explosion indicates that the waves may consist of the fragments of aluminum canister which have been dispersed at extremely high velocity.

Introduction One of the phenomena commonly witnessed during the Firefly releases in the spring of 1959 was the propagation of a faintly white, luminous spherical cloud prior to the growth of the cloud containing alkali metal vapor.

It was observed to grow at a high velocity and to have a life of approximately one second. The phenomenon was associated with those releases in which high explosive was the principal ingredient, and therefore supported conjecture that the observation might have been of a shock wave produced by rapid expansion of the gaseous and solid explosion products.

Instrumentation In the fall, 1959, Firefly series, one of the instruments employed for viewing the releases consisted of a closed circuit TV system built and operated by the Friez Division of Bendix Corporation. This system included an image orthicon tube for viewing, a 21 inch monitor displaying 1029 scan lines, and a 16 mm camera operating at 15 frames per second for photographing the monitor screen. Direct photography of the cloud growth was also provided by K-24 cameras, f/2.5, at 1 second exposure and by Eyemo 35 mm motion picture cameras operated at 4 frames per second and equipped with f/1.1, 50 mm lenses. During the summer, 1960, Firefly series, the same types of instruments were used, with some changes: for example, the closed circuit TV equipment was photographed on 16 mm film at a frame rate of 24 frames per second.

Observations The ability of the foregoing equipment to detect and record the passage of the high velocity wave depended upon the characteristics of the wave and of the specific instrument. An example, typical of most bursts, is afforded by Firefly Cocoa, a cesium vapor burst released on September 30, 1959, at 123.8 km altitude. Figure 1 shows the burst as it appeared in the first exposed frame in a K-24 camera viewing it from a direction west-northwest at a slant range of approximately 150 km. The distance between the fiducial grid lines, evident in the photograph, corresponds to 10 km. The exposure was of one second duration, and can be deduced from other data to have lasted from 0.5 second after burst to 1.5 seconds after burst. The photograph consequently had integrated what was visible during that time. Radial striation is evident, suggesting heterogeneity of the burst constituents. A plot of the density distribution along a radius would appear approximately as shown in Figure 2, which is presented here in case the low contrast of the photograph causes difficulty in reproduction. The hot core is clearly evident, surrounded by three zones, each of which is rather uniform in density despite the long exposure.

Film strips from the Eyemo cameras, though incapable of being reproduced in this article or even of yielding accurate measurements, show in projection a faintly luminous ring spreading out at high velocity from the hot core of the burst.

The photographic record of the television viewing and monitoring system furnished the best quantitative data of all. Although reproductions of these photographs are not presented in this article, they are reported elsewhere by Bang [1961]. In general they tend to show the same structure as that displayed in Figures 1 and 2, despite the fact that exposure time is so short as to avoid the photographic integration of growth. In some cases, as in the picture shown by Bang and pertaining to another burst, zones 2 and 3 (see Fig. 2) are indistinguishable.

Measurements of the outer diameter of two rapidly propagated waves have been derived from Mehr's report [1959] and are displayed in Figure 3. These pertain to Firefly Cocoa, the same burst as pictured in Figure 1. The faster of the two waves, the type with which this report is mainly concerned, showed virtually linear growth at a radial rate of 3.8 km/sec, until it disappeared at the end of 1.6 seconds. The second wave also grew at a nearly constant rate of 0.9 km/sec during the life of nearly 10 seconds.

The material exploded in Firefly Cocoa, like the majority of the Firefly series of chemical releases, was composed of 19 kgm of an intimate mixture of aluminum, an alkali metal compound, and a high explosive, and was therefore somewhat heterogeneous. In contrast to this shot was Firefly Carry, composed wholly of 19 kgm of high explosive in a 9.6 kgm aluminum canister. As indicated in Figure 4, this burst gave rise to a single wave growing at the linear radial rate of 4.5 km/sec before disappearing from the film at the end of 0.6 second. The burst occurred at 129 km altitude and was viewed from a northeasterly direction at a slant range of 134 km.

Both Carry and Cocoa were released substantially above the solar shadow of the earth which was at 119 km and at 88 km altitude, respectively, while the viewing sites were in darkness. The material exploded in Firefly Arlene was similarly composed purely of a high explosive but in contrast to Carry it was released at 104 km altitude in darkness, with the solar shadow at 260 km. From photographs of Arlene taken with K-24 cameras, the luminous cloud reached a maximum radial growth of 100 meters, suggesting that the rapidly cooling core was the only source of illumination. Rosenberg [1961] has pointed out that "this [difference in the two high explosive releases] is one of the reasons for inferring that the rapidly moving radial wave is indeed a particle wave rather than an ionizing shock wave."

Discussion In striving to find the cause of the high velocity wave, it was found desirable to focus attention on Carry. The smaller list of explosion products, the simpler caloric equation of state, and the evidence of only one wave following detonation, all suggested that this might be a simpler phenomenon than that represented in Cocoa. In Carry, there were only two main components: the explosive (RDX) and the aluminum canister in which it was packed.

Taylor's work on explosives, coupled with information on the weight and size of the charge and canister in Carry, permitted computation of the pressure (52,000 atmospheres) and temperature (4300°K) immediately following detonation. The velocity of the detonation wave is approximately 7000 meters per second in loosely packed granular RDX: in the 6.5 inch diameter, 36 inch long canister, detonation would be completed in about 100 microseconds. Even within this time, however, rupture of the canister would have started at that portion of the canister wall nearest the point at which detonation was initiated.

The size of the fragments resulting from rupture may be estimated by considering failure of the wall in tension. From any arc of fragment, a further fragment will be separated so long as the tangential force caused by pressure difference exceeds the ultimate tensile strength of the material. Since the external pressure is negligible,

$$P \int_0^{A/2} r \sin \theta \quad d\theta = Tt$$

leads to an arc length

$$A = 2 \cos^{-1} \left(1-(Tt/r\ P) \right)$$

where T, t, r, and P are respectively the ultimate tensile strength, thickness, and radius of the canister, and P is the internal pressure. This analysis leads to the conclusion that the canister should break, ideally, into approximately 2000 pieces during the course of the burst. This number is sufficiently large that one might expect it to give the appearance of a continuous surface, yet it is small enough that slight deviations from the ideal might give the radially striated appearance observed.

In order to determine how fast the fragments would be thrown outward by the explosive gases, Brode's work on the blast from high explosive was studied. His findings for shock waves cannot be extended to the Firefly series because, as he indicates, a radical difference in density of ambient atmosphere prevents the extension of results which were computed for an explosion at sea level. On the other hand, the physical properties computed over time and space inside the shock wave would be valid in an atmosphere less dense than that at sea level.

Accordingly, equations were fitted to those of Brode's curves shown in Figure 5 for the period soon after burst, in order to be able to express the forces acting on a fragment. Although the fit was crude, an attempt was made to make it best at those places and times at which it was believed, a priori, that the fragment might be found.

These fitted equations were:

$$P = \exp\,[-.00112\ rt^{-1} + 10.9 - 50{,}600.t + 101{,}000{,}000.t^2].$$

$$D = \exp\,[-.00112\ rt^{-1} + 7.3 - 20{,}500.t + 25{,}000{,}000.t^2].$$

$$V = 132000\ (r + .01) \quad \text{for} \quad 0 \leq t < .000007$$

$$V = 1320 + .023\ rt^{-1} \quad \text{for} \quad .000007 \leq t$$

where P = pressure, atmospheres

D = density, kilograms per cubic meter

V = velocity, meters per second

r = radial displacement from initial position, meters

t = time after burst, seconds

The equation of motion for a fragment was then expressed under the following assumptions:

1) That the fragment would be located at the periphery of the explosive sphere at the instant of burst.
2) That the forces acting upon the fragment would be those due to pressure and drag.
3) That the pressure on the outer side of the fragment would be negligible.
4) That the resistance offered by the fragment upon the gas would not change the functions of P, D, and V represented above.

Of these assumptions, only the last appears to be much at variance with the facts, since the area at burst completely encloses the charge, and since the mass of the fragments is nearly one half that of the explosive. Establishing the equation of motion upon these assumptions, nevertheless, one obtains

$$\ddot{r} = \left((C_D/2)\ D(V-\dot{r})\ \left| V-\dot{r} \right| + Pk \right)\ a/m$$

where m, a, $\dot{r}$, $\ddot{r}$ are the mass, frontal area, velocity and acceleration of the fragment, C_D is the drag coefficient, taken as 1.28, and k is a conversion factor from atmospheres to mks units.

The result of integrating a difference equation corresponding to the one in the previous paragraph on a Burroughs 220 computer was to yield a fragment velocity exceeding 2500 meters per second. Furthermore, this velocity was achieved within less than a millisecond following burst.

Inasmuch as the action of the fragment upon the gas behind it will be to prolong the high pressure--contrary to the fourth assumption made above--the velocity might be expected to be higher than that computed. On the basis of the foregoing indication, it appeared desirable to establish a more accurate physical model: this would consider the spherical burst as contained within the fragmenting shell except insofar as cracks in the latter permitted the gas to escape. Under such a condition, computation shows that the fragment may achieve a velocity exceeding 3300 meters per second.

Conclusion The conclusion to be reached from these computations is that the high velocity wave observed by the image orthicon instrumentation may indeed be caused by fragments of canister being blown out. Once they have been accelerated to that velocity, the fragments would not be measurably slowed by the rarefied atmosphere at the burst altitude. During the half second that the wave from Carry is visibly expanding, it travels little over 2000 meters. In view of the(ARDC model atmosphere) density of 6.44×10^{-9} kilograms per cubic meter at the burst altitude, this density implies that a fragment of 3 square centimeters area and 5 grams mass would sweep out a volume encompassing a mass of only 4×10^{-6} grams during its half-second travel, if the fragment is assumed to remain intact during this time. It is apparent that the fragments could have a markedly higher ratio of area to mass without seriously conflicting with the linearity of growth which is evident in Figures 3 and 4. By the same token, they do not encounter enough mass of air to undergo further appreciable chemical reaction: whatever oxidation occurs must seemingly do so within the few microseconds during which the fragments first are passed by, then pass, in their turn, the explosive products as these become slowed by the ambient atmosphere.

Further work remains to be done in order to confirm other aspects of the foregoing which must currently be categorized as conjecture. It is apparent that the fragmenting canister can cause some of the observed results: it remains to be shown that the observed phenomena necessarily follow from the experimental conditions.

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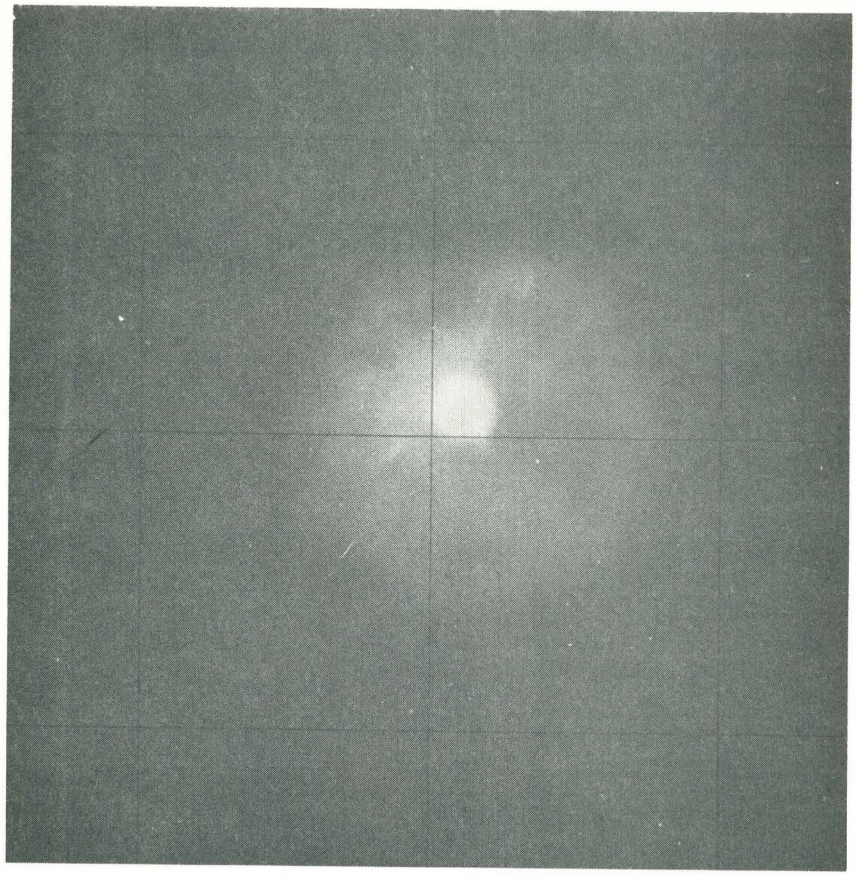

Figure 1. Firefly Cocoa, as photographed by a K-24 camera with one second exposure.

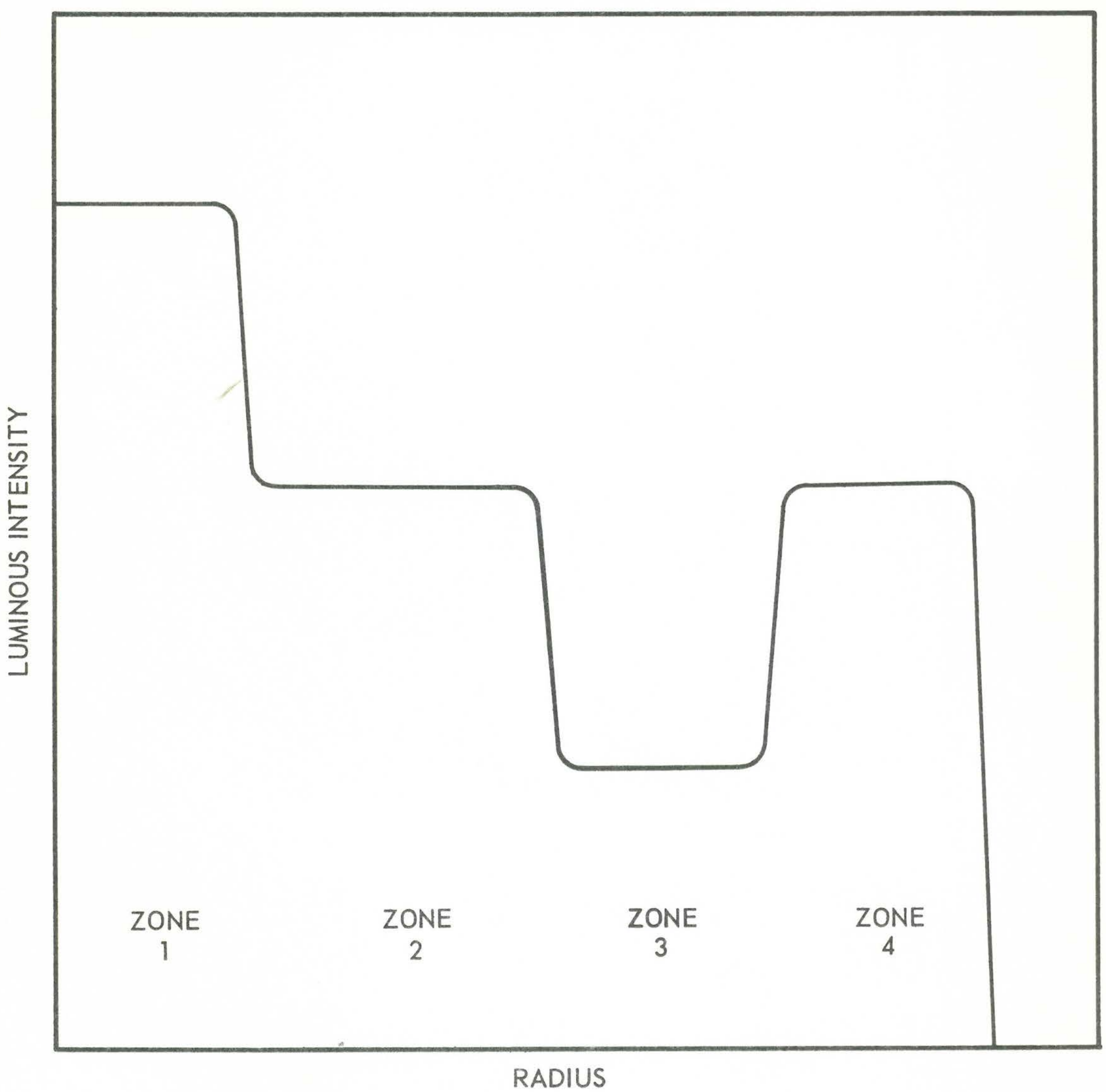

Figure 2. Zones of luminous intensity visible in the photograph of Firefly Cocoa shown in Figure 1.

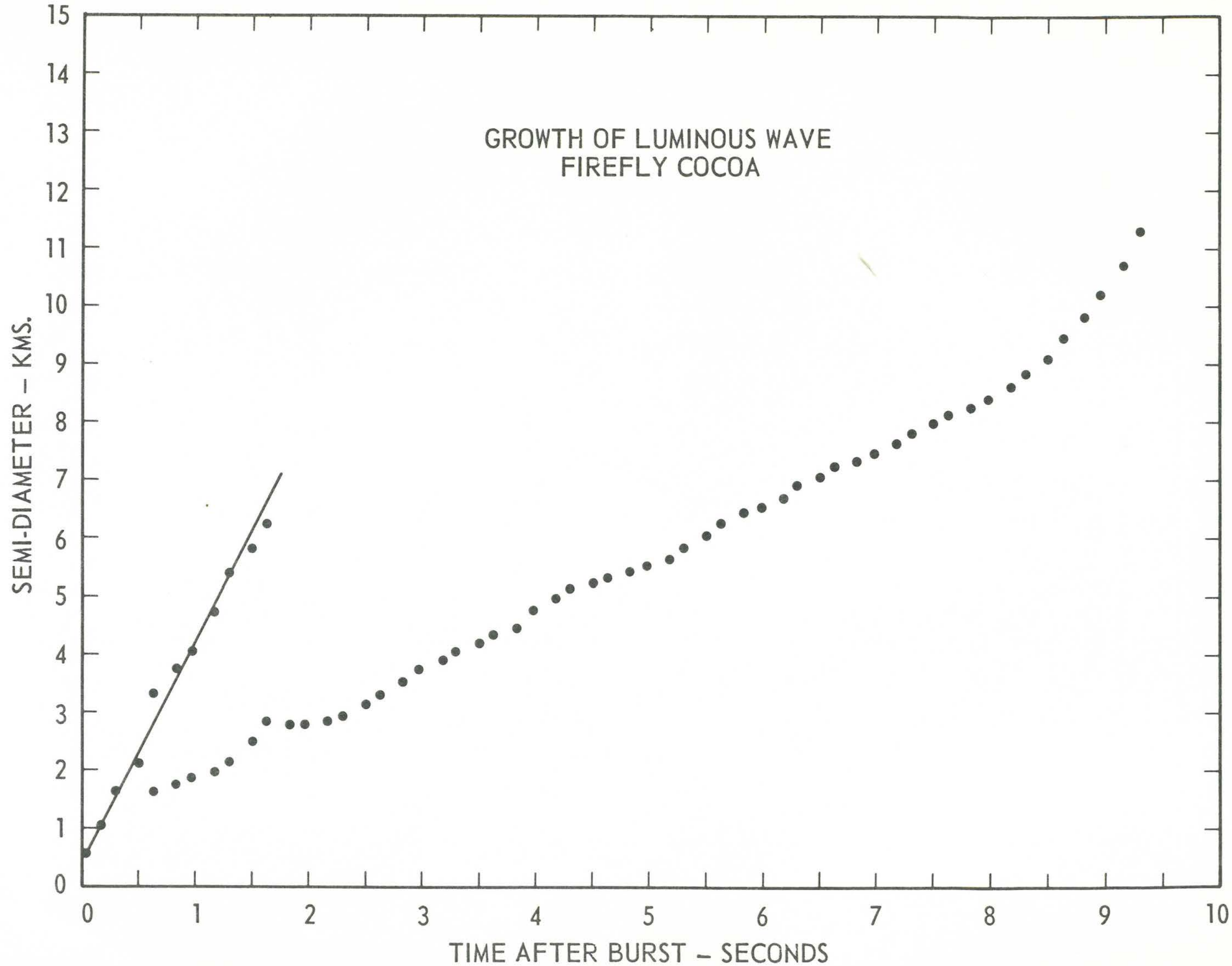

Figure 3. Measurements of the luminous waves of Firefly Cocoa, as observed by means of closed-circuit television.

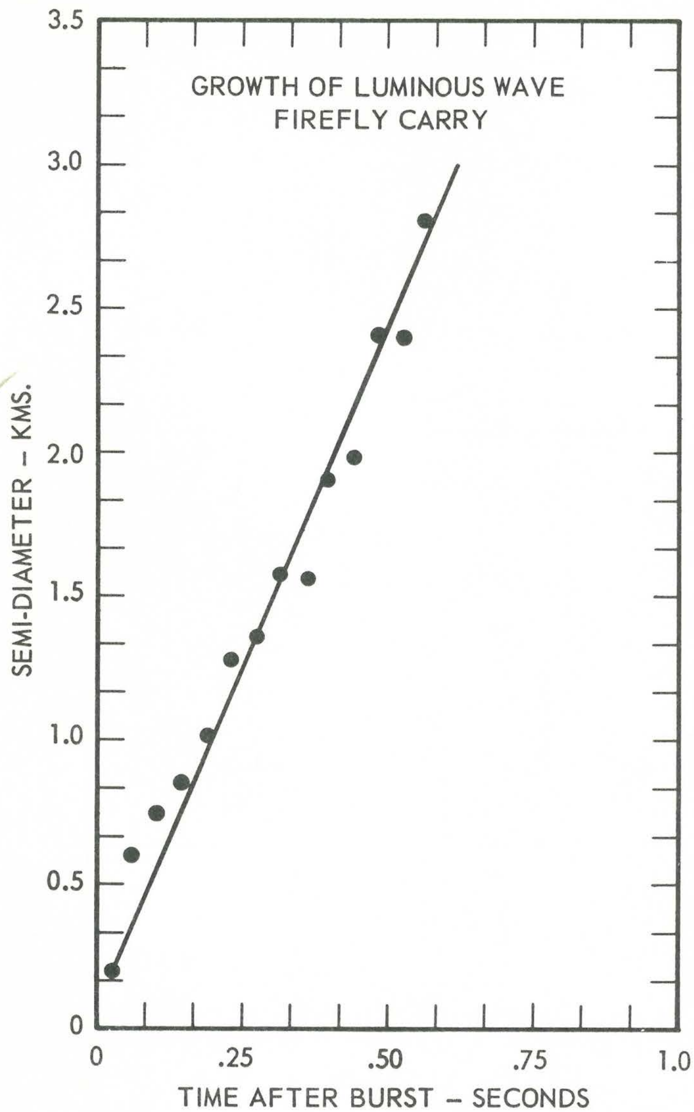

Figure 4. Measurements of the luminous wave of Firefly Carry, as observed by means of closed-circuit television.

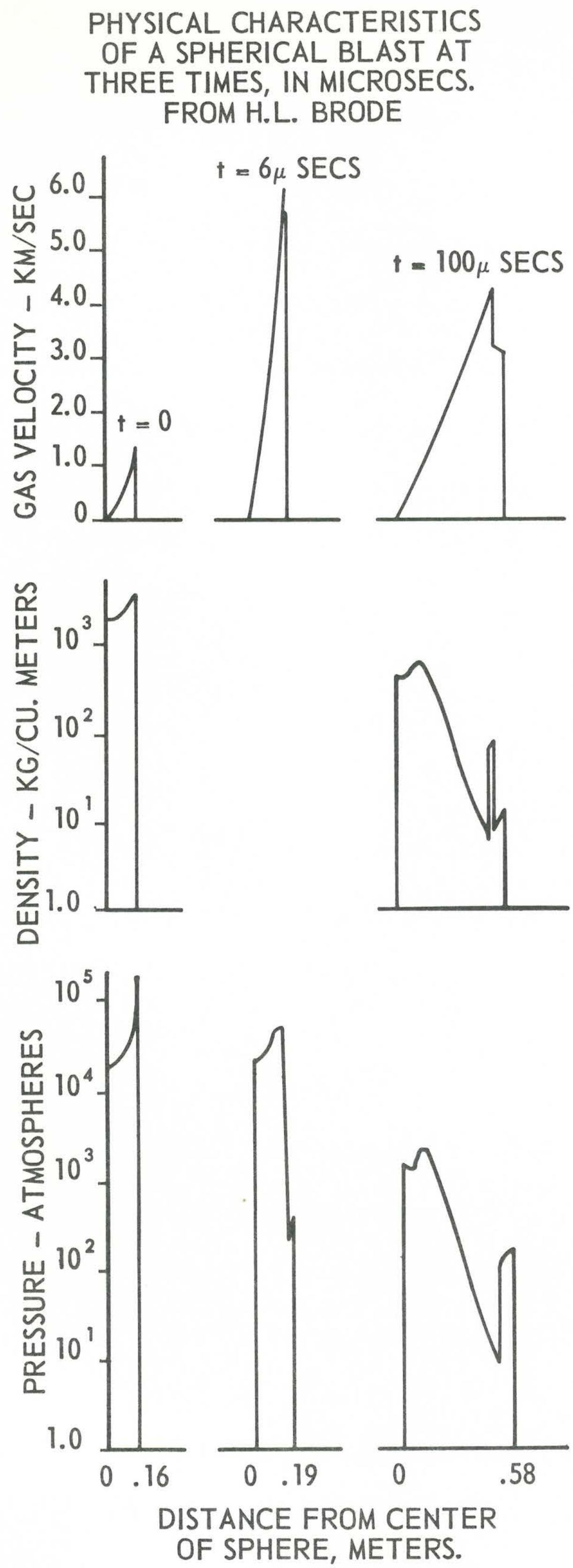

Figure 5. Physical characteristics of a spherical blast at sea level, at three times starting with completion of detonation. (Brode, 1959).

APPENDIX 2

Computer Data Processing Procedure

There are two basic computing programs associated with the filter-wheel photometer. For one of them, the signal recorded by the galvanometer is transcribed to IBM cards, in the form of nine measurements (one for each filter), the time at which the first of the filter signals occurred, a rocket identification, and a code number which shows whether the signal is believed to be radiance from the sky background or from a source. From this input and using characteristics of the photometer determined by calibration, the program computes the radiance sensed by each filter relative to the response of the photomultiplier tube at the wavelength to which it is most sensitive. At the option of the analyst, the radiance so computed for each filter is then divided by a normalizing quantity, the total radiance which would have been sensed by the filter in a continuum having the same radiance at all wavelengths. If only a continuum has, in fact, been observed, the foregoing quotient represents it to a first approximation. If the output is printed, by choice, in unnormalized radiance, on the other hand, it is directly proportional to the excess of the galvanometer reading above background. In this case, the set of photometric responses through the several filters must be compared to a similar set arising from a hypothetical spectrum if the hypothesis is to be tested.

Computation of the set of filter responses which would arise from a hypothetical spectrum is achieved by a second program. In this, each of the filters is represented piecewise or in toto by an analytical expression which has been fitted to the filter fractional transmission as a function of wavelength, $O(\lambda)$. In the same way, the transmission of the collimating lenses used with the filter $C(\lambda)$, has been measured as a function of wavelength, as has the response $P(\lambda)$ of the photomultiplier tube (6810A) used in the 1962 releases: both of these are represented by analytical expressions in the program.

Starting with a hypothetical spectrum introduced in the program either in piecewise form as a set of tables, or as an analytical function of $R(\lambda)$ wavelength, the program computes the magnitude of the response at each wavelength at the photocathode of the photomultiplier tube. Allowance is made for atmospheric absorption by means of a tabular transmission function $F(\lambda)$, so that the hypothetical spectrum may be represented as it would appear within the release itself. In computing the response over the range of the photomultiplier tube, the program integrates this response and computes the mean wavelength of response for each filter: the latter is, of course, slightly dependent upon the hypothetical input spectrum for continua and would be especially so if an intense line were present.

One form of hypothetical input--uniform flux at all wavelengths--was employed in order to obtain normalizing transmission factors for the several filters, for use in the data processing program previously described. Each factor represents the response of the photocathode to radiant flux through the filter with which that factor is associated, if there is no prior knowledge about the dependence of radiant flux upon wavelength.

Another form of hypothetical input which has been used is the Planck distribution of black-body radiation, with provision for determining the effect of different temperatures upon the filter response. Part of the reason for introducing this form of hypothetical radiant input was to determine the degree to which Rayleigh-scattered sunlight (6300°K) accounted for background radiance at increasing angles of solar depression: this work has been sidetracked in the hope that a sponsor may be found, while continuing in the search for evidence of shock waves. Another reason was that many of the releases used in these atmospheric experiments have employed reactive mixtures of which half the weight of reaction products are solids or liquids even at the high temperatures involved, and from which a continuum may therefore be plausibly expected.

APPENDIX 3

Near the close of the grant period, studies were begun on a Ph.D. dissertation in the School of Physics on upper atmosphere diffusion. Here, unlike the shock wave problem, photographic data were already available and the study did not depend on future field observations.

Initial and Projected Work on Upper Atmospheric Diffusion

At the outset, photographs of point releases of sodium were used to determine the coefficient of diffusion at the release altitude. The diameter of the diffusing sphere of sodium was determined by a simple overlap comparator. The growth rate led to the diffusion coefficient. However, the numbers obtained were of questionable value due to the large errors inherent in the diameter measurement.

Future measurements will be made by means of a microdensitometer. The analysis is planned to include not only point releases at a variety of altitudes, but also trails of sodium vapor which extend many kilometers in altitude. Present methods exist for the precise determination of position of either point releases or portions of a trail cloud.

In regions of high turbulence, the clouds break into small globules several kilometers in diameter. Precise measurements of position and growth rate are expected to yield data pertinent to turbulent diffusion.

This work is being continued under a grant from NASA.